P5.8 INTERCOMPARISON OF THREE SEA SURFACE ROUGHNESS SCHEMES USING BUOY DATA

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1. INTRODUCTION

There are two fundamental issues in surface flux parameterization: (1) the dependence of fluxes on the determination of roughness lengths, and (2) the relationship between the fluxes and the atmospheric stability. While there are many ways of representing the stability dependence of surface fluxes, all are based on Monin-Obkhov similarity and empirical formulations of the non-dimensional vertical gradient of temperature and water vapor, and on the vertical shear of the mean wind (e.g., Louis 1982, Fairall *et al*., 1996). The representation of the sea surface roughness, on the other hand, varies significantly. This is particularly true for the aerodynamically rough flow under moderate to strong wind regime.

The typically used scheme of z_0 for an aerodynamically rough flow is the so-called Charnock relationship: $z_0 = z_{ch} u_*^2 / g$ (e.g., Charnock, 1955, and Yelland and Taylor 1996), where g is the acceleration due to gravity, u_* velocity scale for surface stress, and z_{ch} is the Charnock parameter. Numerous previous studies resulted in various values of the Charnock parameter for fetch-limited conditions or over lakes (e.g., Hsu, 1974). It thus became obvious that the role of the wave-induced surface stress should be incorporated into the momentum flux parameterization. The question is then which variable or a combination of variables one should use to obtain a formulation that is widely applicable under various conditions. Wave age and wave steepness are the two most relevant variables.

Recently, Taylor and Yelland (2001, hereafter TY01) proposed that the sea surface roughness z_0 can be expressed in terms of height and steepness of the waves defined as h_s / c_w, where h_s is the significant wave height and c_w is the phase speed of the wave. Their formulation of z_0 was found to be applicable to measurements from a variety of conditions including wave tanks, lakes and the open ocean. Their results suggested the dominant role of wave steepness in comparison with the wave age defined as c_w / u_*, or c_w / u, where u_* is the frictional velocity scale and u the mean wind speed. Oost et al. (2001, hereafter O01), on the other hand, emphasized the role of wave age in addition to steepness and proposed a formulation of z_0 as a function of wave age and u_*. Both formulations are now included in the latest version of COARE algorithm originally developed using the measurements from TOGA COARE (Fairall *et al*., 1996 and 2001). In addition, the latest COARE algorithm also included an option where the fixed value of the Charnock parameter (0.011) in the previous version of COARE algorithm was replaced by a linear formulation with a simple wind-speed dependence between 10 ms^{-1} and 18 ms^{-1} based on data from Yelland and Taylor (1996) and Hare *et al*. (1999). This scheme will be referred to as YT96. These three options for z_0 are listed in Table 1 for easy reference.

Significant wave height and peak wavelength for the wave spectrum are measured quantities from the buoys of the National Data Buoy Center (NDBC). The TY01 and O01 algorithm thus provide us two independent methods of estimating the surface roughness height from the NDBC buoys using the significant wave height and dominant wave period. However, we have found no direct comparisons of the three schemes in Table 1 from previous studies. The objectives of this study is thus to understand the sensitivity of the buoy-derived surface momentum fluxes to choices of surface roughness parameterization and understand the range of applicability of the three schemes. We will use the stability dependence scheme in the COARE algorithm with each of the roughness schemes listed in Table 1 in our calculation of the surface stress so that the differences in surface stress are caused by different ways of roughness calculation.

2. THE BUOY DATA

The data used to drive the bulk parameterization schemes in this research, were collected at a National Data Buoy Center (NDBC) 3-m Discus buoy site numbered as 44008 (hereinafter referred to as B44008) from January 1 through February 10, 2000. B44008 was at the site (40.5^{0}N, 69.43^{0}W) about 50 km off the coast of Connecticut in the Atlantic Ocean. The water depth reaches 62.5 m at this site. Hourly measurements at the buoy include horizontal wind speed and direction at 5.0 m above seal level (*asl*), air temperature and dew point temperature at 4.0 m *asl*,

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barometric pressure at sea level, sea surface temperature at the depth of 0.6 m below sea surface, significant wave height h_s, and dominant wave period t_w). These quantities and the calculated bulk Richardson number are shown in Fig. 1 for the period.

Table 1 The momentum roughness length algorithms for rough flow to be discussed in this paper. Here, u is the wind speed at the 10 m height; l_p, h_s, and c_w are the peak wavelength for the combined sea and swell spectrum, significant wave height, and phase speed at the peak of the wave spectrum respectively.

Name	Formula
YT96	$z_0 = \frac{z_{ch} u_*^2}{g}$, where, $z_{ch} = \begin{cases} 0.011, & u \le 10ms^{-1} \\ 0.011 + \frac{0.007(u-10)}{9}, & 10ms^{-1} < u \le 18ms^{-1} \\ 0.018 & u > 18ms^{-1} \end{cases}$
O01	$z_0 = \frac{25}{\pi} l_p (\frac{u_*}{c_w})^{4.5}$
TY01	$z_0 = 1200 h_s (\frac{h_s}{l_p})^{4.5}$

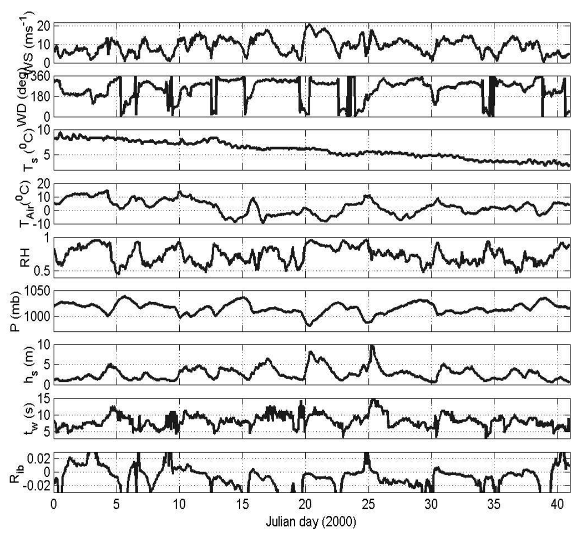

Figure 1 Hourly meteorological data for 1 January – 10 February 2000 from the NDBC buoy B44008.

Figure 1 clearly shows the increase of wind speed and significant wave height, the decrease of air temperature in response of the low-pressure system during the winter storm passage. The average horizontal wind speed was 9.1 ms^{-1} with the maximum wind speed of about 21 ms^{-1} on Julian day 20, 2000. The average sea bulk temperature was 5.9 ^{0}C and the average air temperature was 2.4 ^{0}C. Relative humidity was derived from the dew point temperature and air temperature, and its average was 0.73. The average significant wave height h_s was 2.69 m, and the maximum of h_s reached 9.72 m. The average dominant wave period t_w was 8.16 s, and the maximum reached 14.29 s. Details on the instruments and various data processing techniques are given from the following website: http://www.ndbc.noaa.gov/measdes.shtml.

3. RESULTS

In order to ensure that the differences among results were solely from the parameterizations of roughness length, we fixed other parts of the COARE algorithm to be the same prior to testing. The variation of the resultant friction velocity u_*, roughness length z_0, and the neutral drag coefficients C_{DN} with respect to wind speed at 10 m height from all three roughness schemes in Table 1 are shown in Fig. 2.

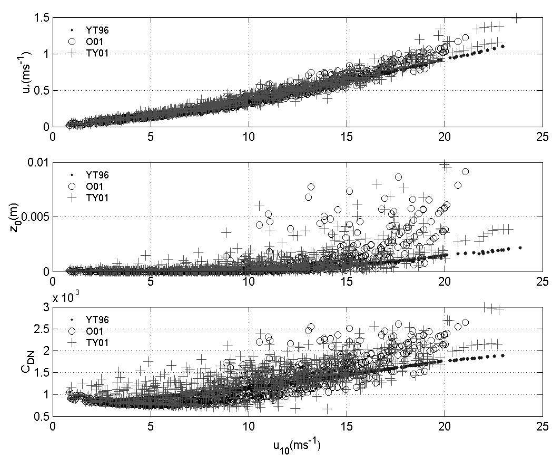

Figure 2 Variations of friction velocity u_*, roughness height z_0, and drag coefficient C_{DN} with wind speed at 10 m height. Results for all three schemes for roughness length in Table 1 are shown.

Figure 2 shows that three schemes in general produce rather similar results in u_*, z_0, and C_{DN} in small to moderate wind speed. At high-wind speed (e.g., wind speed greater than 15 ms^{-1}), large scattering are observed within each scheme and among schemes. Among the three schemes, YT96 seems to give the smallest z_0 with the least scattering. A more detailed comparison is shown in Fig. 3, where conditions with wind speed greater than 18 ms^{-1} or when the inverse of wave age (u_*/c_w) is greater than 0.06 are plotted using a different symbol. The values of 0.06 for u_*/c_w was chosen because this value appeared to separate the results into two groups where deviations between the TY01 or O01 schemes and the YT96 scheme are most evident when u_*/c_w >0.06, i.e., when the wave age was comparatively young. Considering that YT96 does not include any explicit wave age dependence in the Charnock parameter above 18 ms^{-1}, it is not surprising to find discrepancies between YT96 and TY01 or O01 beyond 18 ms^{-1}. However, Fig. 3 also shows that the discrepancy between YT96 and the other two schemes are consistently seen in the young waves (lower panels, circles) in both high wind and moderate wind conditions. TY01 and O01, especially O01, clearly incorporate more wave age effects than YT96.

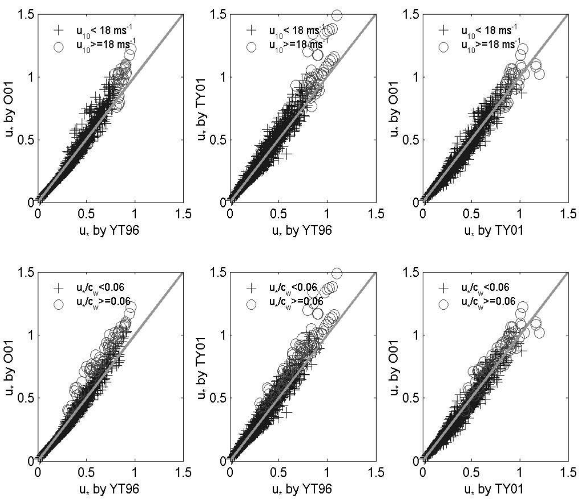

Figure 3 Inter-comparison of friction velocity using three schemes of roughness length.

Figure 3 shows consistent results between TY01 and O01 in all wind speed regimes and for all wave ages. This is explained by Fig. 4, where the wave steepness correlates well with the wave age with a correlation coefficient of 0.83. If the low wind speed (wind speed less than 6 ms^{-1}) is excluded from this calculation to ensure a rough sea, the correlation coefficient becomes 0.84. Thus, for the observations at the buoy, the waves with large steepness are mostly young waves in terms of wave age. The TY01 and the O01 schemes hence work equally well for this particular dataset.

4. DISCUSSION

Although both TY01 and O01 work well for this particular dataset, there are subtle differences among all three schemes. Figure 5a shows the variation of the neutral drag coefficients from the TY01 scheme as a function of time. We noticed that C_{DN} appears to indicate some discontinuity when it increases from a local minimum. In contrast, YT96 and O01 schemes

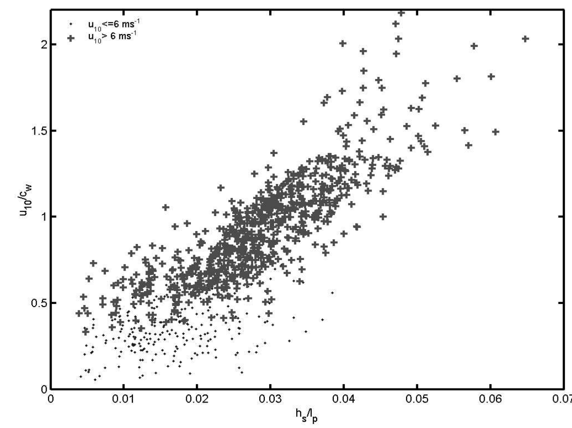

Figure 4 Relationship between wave age parameter (u_{10}/c_w) and wave steepness (h_s/l_p).

both generate a smooth temporal variation with time (not shown). To understand this behavior of the TY01 scheme, we plotted the time variation of the wave steepness and the inverse of the wave age in Fig. 5b and 5c. Here, we found that the discontinuity is associated with sudden increases in wave steepness and the young waves. Comparing to the variations of wind speed and direction, the young waves occurred mostly at the onset of the a storm when the wind speed started to increase from its minimum value or when there is rapid change in wind direction (Fig. 1), which are conditions favorable for the formation of young waves. In general, we do not expect discontinuities in the time variation of a physical parameter such as the exchange coefficient. It may reflect the weakness of the scheme in the presence of very young waves. Unfortunately, we do not have direct turbulence measurements to evaluate the validity of the TY01 schemes in these conditions.

In calculating the momentum flux using the implicit iteration method, no physically meaningful solution can be found around 0000 UTC on Julian day 20, 2000 using the O01 scheme after 8 iterations, while normally three iterations are sufficient to converge to a solution. It is worth noting that this is the time when the youngest wave were found (Fig. 5c) corresponding to rapid increase of wind speed at the onset of a winter storm (Fig. 1). It appears that the O01 scheme may experience difficulty in case of very young waves as well.

We should mention that the three schemes were used for all wind conditions during the measurement period, including those when the wind speed were less than 6 ms^{-1}. Since the schemes are for the rough sea roughness height, they may not produce the correct roughness length for the low wind conditions that favour a smooth sea, even though all three schemes gave consistent results.

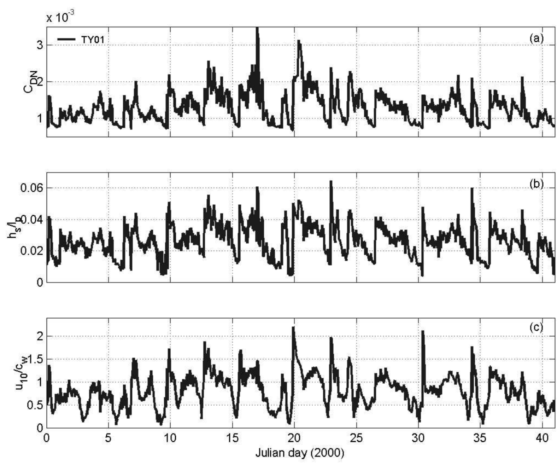

Figure 5. Variation of neutral drag coefficient C_{DN} , wave steepness h_s/l_p , and the inverse of wave age u_{10}/c_w . The TY01 roughness scheme is used.

5. SUMMARY AND CONCLUSIONS

The TY01 and O01 formulations of surface roughness provide additional methods of estimate surface roughness height from the NDBC buoys using independent measurements. We have used 40 days of measurements from an offshore buoy during the wintertime to examine the differences in surface stress resulting from different formulations of surface roughness (YT96, TY01, and O01 schemes). Our results suggested the similarity between TY01 and O01 for this particularly measurements as a result of the strong correlation between the wave steepness and the wave age. The YT96 produces different results of surface stress, particularly in high wind conditions, because the wave age effects are not considered when wind speed is above 18 ms^{-1}. For wind speed below 18 ms^{-1}, the YT96 scheme tend to underestimate the frictional velocity when the waves are relatively young. We also found that O01 scheme may experience numerical problems in case of extremely young waves while the YT01 scheme frequently resulted in discontinuity in the neutral drag coefficients for young waves.

With a distance of about 50 km from the coast and a water depth of 63 m, and the fact that wave steepness correlate well with the wave age, the conditions for our study is likely representative of an open ocean with no swell condition. Similar study is desirable for the coastal buoys to further identify the nature of the three roughness parameterizations, which will be the focus of our future effort.

6. ACKNOWLEDGMENT

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